

USING WINTER COVER CROPS TO IMPROVE SOIL AND WATER QUALITY

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ABSTRACT

This article reviews literature about the impacts of cover crops in cropping systems that affect soil and water quality and presents limited new information to help fill knowledge gaps. Cover crops grow during periods when the soil might otherwise be fallow. While actively growing, cover crops increase solar energy harvest and carbon flux into the soil, providing food for soil macro and microorganisms, while simultaneously increasing evapotranspiration from the soil. Cover crops reduce sediment production from cropland by intercepting the kinetic energy of rainfall and by reducing the amount and velocity of runoff. Cover crops increase soil quality by improving biological, chemical and physical properties including: organic carbon content, cation exchange capacity, aggregate stability, and water infiltrability. Legume cover crops contribute a nitrogen (N) to subsequent crops. Other cover crops, especially grasses and brassicas, are better at scavenging residual N

before it can leach. Because growth of these scavenging cover crops is usually N limited, growing grass/legume mixtures often increases total carbon inputs without sacrificing N scavenging efficiency. Cover crops are best adapted to warm areas with abundant precipitation. Water use by cover crops can adversely impact yields of subsequent dryland crops in semiarid areas. Similarly, cooler soil temperatures under cover crop residues can retard early growth of subsequent crops grown near the cold end of their range of adaptation. Development of systems that reduce the costs of cover crop establishment and overcome subsequent crop establishment problems will increase cover crop utilization and improve soil and water quality.

INTRODUCTION

Cover crops are traditionally defined as crops grown to cover the ground to protect the soil from erosion and from loss of plant nutrients through leaching and runoff (Reeves, 1994). Additional reasons for growing cover crops include weed suppression, carbon sequestration, and integrated pest management. Cover crops can protect water quality by reducing losses of nutrients, pesticides, or sediment from agricultural fields. Soil erosion leads to reductions in soil quality and productivity (Pierce and Lal, 1994). Wind erosion rates of less than 1 t/ha can cause serious crop injury (Hayes, 1965) and damage on sandy soils has increased in recent years where fields have been enlarged by removing tree lines to facilitate center-pivot irrigation systems. No-till management greatly reduces wind and water erosion, but some question its influence on water quality (Shipitalo et al., 1997).

In this paper, we follow a literature review with information from specific experiments and conclude with some observations concerning practical management issues. We try always to keep in mind that cover crops are planted by farmers whose first priority is frequently economic survival. A farmer's choice to include cover crops in cropping systems is based on the perceived balance between advantages and disadvantages (Table 1). The fact that only a very small percentage of U.S. cropland is currently planted with cover crops suggests that most producers find the disadvantages more evident than the advantages. This paper attempts to highlight research showing the biophysical and economic benefits of including cover crops in alternative production systems that may become more prominent in the future.

Table 1. Advantages and Disadvantages of Cover Crops

Advantages
Reduce soil erosion
Increase residue cover
Increase water infiltration
Increase soil organic carbon
Improve soil physical properties
Improve field trafficability
Recycle nutrients
Legumes fix nitrogen
Weed control
Increase populations of beneficial organisms
Reduce some diseases
Increase mycorrhizal infection
Potential forage harvest
Improve landscape aesthetics

Sediment

Sediment is agricultural soil that is eroded (Reeves et al., 1993). Even on relatively flat land, sediment erosion often exceeds tolerable levels. Cover crops can reduce sediment concentration in runoff, reduce more biomass than bare soil, and allow more rainfall to infiltrate the soil, reducing erosion to a greater extent. This paper examines the impacts of cover crops on sediment erosion from the impacts of cover crops on sediment erosion breakdown. By slowing down the erosion rate, cover crops can reduce the sediment concentration in runoff. Mutchler and McDowell (1991) and Decker et al. (1991) found that cover crops can reduce sediment erosion by 50% or more.

Nutrients

Cover crops can improve soil fertility (Reeves et al., 1991; Lal, 1997; Delgado, 1998). Besides the benefits of cover crops to soil fertility, cover crops can also improve soil structure and water infiltration.

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Table 1. Advantages and Disadvantages of Using Cover Crops

Advantages	Disadvantages
Reduce soil erosion	Must be planted when time (labor) is limited
Increase residue cover	Additional costs (planting and killing)
Increase water infiltration into soil	Reduce soil moisture
Increase soil organic carbon	May increase pest populations
Improve soil physical properties	May increase risks of diseases
Improve field trafficability	Difficult to incorporate with tillage
Recycle nutrients	Allelopathy
Legumes fix nitrogen	
Weed control	
Increase populations of beneficial insects	
Reduce some diseases	
Increase mycorrhizal infection of crops	
Potential forage harvest	
Improve landscape aesthetics	

Cover Crops and Water Quality

Sediment

Sediment is agriculture's number one pollutant (National Research Council, 1993). Even on relatively flat lands such as the Mississippi Delta, water erosion often exceeds tolerable levels (Murphree and McGregor, 1991) and excessive sediment concentration limits fish growth (Dabney et al., 1999). Cover crops produce more biomass than volunteer vegetation and, therefore, transpire more water, allow more rainfall to infiltrate into the soil, and decrease runoff and potential erosion to a greater extent (Dabney, 1998). In addition, cover crops protect aggregates from the impacts of rain drops, reducing soil detachment and aggregate breakdown. By slowing wind and water velocities and by maintaining large aggregate size, cover crops greatly reduce wind and water erosion (Frye et al., 1985; Mutchler and McDowell, 1990; Holderbaum et al., 1990; Bilbro, 1991; Langdale et al., 1991; Decker et al., 1994; Dabney, 1998; Delgado et al., 1999).

Nutrients

Cover crops can increase the nutrient use efficiency of farming systems (Lal et al., 1991; Lal, 1997; Reicosky and Forcella, 1998; Staver and Brinsfield, 1998; Delgado, 1998). Besides reducing the loss of nutrients in eroded soil, cover crops

can scavenge residual soil nitrate nitrogen (NO_3^- -N) after crops have matured, converting scavenged nitrogen into forage protein. The amount and timing of N uptake by cover crops depends on the availability of soil N, the climate, and cover crop species, seeding rate, planting date, and desiccation time (Gallaher 1977; Groffman et al., 1987; Brinsfield and Staver, 1991; Meisinger et al., 1991; Shipley et al., 1992; Clark et al., 1994; McCracken et al., 1995; Delgado et al., 1999). Winter cover crops generally have a period of fall growth followed by a winter period when growth slows or stops. In the spring, rapid growth involves additional N uptake if residual soil N remains available. However, after the boot growth stage, rye cover crops can double in biomass without taking up additional N (Shipley et al., 1992; Clark et al., 1994; Vaughan and Evanylo, 1998). Legume cover crops, which can symbiotically fix atmospheric dinitrogen (N_2), usually accumulate N longer in the spring than non-legume cover crops (Sullivan et al., 1991; Clark et al., 1997a, b; Vaughan and Evanylo, 1998). The objectives of scavenging residual soil NO_3^- -N or adding legume N into the farming system need to be balanced when using cover crops as nutrient management tools.

Rye (*Secale cereale* L.), forage radish (*Raphanus sativus* L.), and canola (*Brassica rapa* L.) have greater potential to scavenge residual soil NO_3^- -N than legume cover crops (Jones, 1942; Chapman et al., 1949; Walker et al., 1956; Jones et al., 1977; Nielsen and Jensen, 1985; Groffman et al., 1987; Meisinger et al., 1991; Shipley et al., 1992; Waggoner et al., 1998; Isse et al., 1999). In part, this may be due to faster root growth (Sainju et al., 1998). With high residual soil NO_3^- -N, legume nodulation and N_2 fixation are decreased (Viets and Crawford, 1950; Allos and Bartholomew, 1955; Schertz and Miller, 1972; Streeter, 1985) and legumes will scavenge some NO_3^- -N (Schertz and Miller, 1972; Morris et al., 1986). In situations where residual N is low, cover crop growth can be N limited. Cereal/legume bicultures are flexible in that they scavenge more NO_3^- -N than legume monocultures, yet produce abundant growth based on N_2 fixation when soil N is limiting (Clark et al., 1994; Ranells and Waggoner, 1997a; Clark et al., 1997a). In situations with large excesses of soil NO_3^- -N, cover crop growth and N scavenging may be limited by solar radiation, temperature, and time. Research to evaluate the importance of cover crop planting date in such situations is presented later in this paper.

Computer models are promising tools for evaluating soil water and nutrient status and for conducting risk analyses of the potential benefits of cover crops in different scenarios. Quemada and Cabrera (1995b) used the CERES-N submodel that describes N transformations of residues decomposing at the soil surface to simulate the decomposition of leaves and stems of crimson clover (*Trifolium incarnatum* L.), rye, wheat (*Triticum aestivum* L.) and oat (*Avena sativa* L.). Bowen et al. (1993) used the CERES-Maize model to simulate the effects of a green manure legume incorporation with conventional tillage in a corn (*Zea mays* L.) rotation. The CERES-Wheat and a modified soybean (*Glycine max* (L.) Merr.)

model were used to simulate winter-riddle et al. (1997) Analysis Package (NL) planting dates on N use efficiency (*Solanum tuberosum*) predictions can be compared

Pesticide Usage

Water quality risk of pesticide applied; pesticide (insecticide, increases depending on cover crops can suppress if cover crops are difficult Dabney, 1990).

Weed suppression adoption of no-till systems 95% in some regions. competition, niche displacement, species, planting date, subsequent crop planting (C) herbicide requirements yet be easier to control management of cover crops with (Derpsch et al., 1991) displace weeds while (Evers, 1983; Hoffmann) Weed control is usual crops are allowed to (1988). Rye residues are to suppress weed growth (1983; Barnes et al., 1991; et al., 2000). Cover crops with no tillage than if (living mulches) have often competitive with and Burrill, 1993; Del therefore, most practice chards (Infante and Mc

) after crops have matured, the amount and timing of N soil N, the climate, and cover rotation time (Gallaher 1977; Meisinger et al., 1991; Shipley 1995; Delgado et al., 1999). Growth followed by a winter growth involves additional cover, after the boot growth but taking up additional N (Evanylo, 1998). Legumes dinitrogen (N_2), usually cover crops (Sullivan et al., 1998). The objectives of scavenging the farming system need to be improved tools.

us sativus L.), and canola residual soil NO_3^- -N than (Walker et al., 1956; Jones et al., 1987; Meisinger et al., 1999). In part, this may be high residual soil NO_3^- -N, (Sims and Crawford, 1950; Altieri and Streeter, 1985) and legumes (1972; Morris et al., 1986). Soil can be N limited. Cereal/legume more NO_3^- -N than legume N_2 fixation when soil N is low (Clark et al., 1997a). In crop growth and N scavenging time. Research to evaluate rotations is presented later in

ing soil water and nutrient benefits of cover crops in the CERES-N submodel using at the soil surface to mon clover (*Trifolium int*) (*Avena sativa* L.). Bowen ate the effects of a green e in a corn (*Zea mays* L.) (*Glycine max* (L.) Merr.)

model were used to simulate a no till winter cover rye—soybean rotation by Wagner-Riddle et al. (1997). Version 1.20 of the Nitrogen Leaching and Economical Analysis Package (NLEAP) has been used to evaluate effects of cover crop planting dates on N use efficiency of a lettuce (*Lactuca sativa* L.)—cover crop—potato (*Solanum tuberosum* L.) rotation (Delgado, 1998; Delgado et al., 1998) and predictions can be compared with the research results presented later.

Pesticide Usage

Water quality risks from pesticides are generally proportional to the amount of pesticide applied; lower application reduces risk. Impacts of cover crops on pesticide (insecticide, herbicide, fungicide) usage can vary from increases to decreases depending on numerous management alternatives. As one illustration, cover crops can suppress weeds and thereby decrease herbicide requirements, or, if cover crops are difficult to control, herbicide rates may be increased (Griffin and Dabney, 1990).

Weed suppression by cover crops has been a key element in the successful adoption of no-till systems in South America (Derpsch, 1998), which has reached 95% in some regions. Weed suppression by cover crops can be due to resource competition, niche disruption, and phytotoxic effects and is affected by cover crop species, planting date, seeding rate, kill method, and kill timing relative to subsequent crop planting (Creamer et al., 1996; Liebman and Davis, 2000). To reduce herbicide requirements, cover crops must be competitive with native vegetation yet be easier to control as main crop planting time approaches. Mechanical treatment of cover crops with mowers or rolling choppers can reduce herbicide inputs (Derpsch et al., 1991; Dabney et al., 1991; Creamer et al., 1995). Cover crops displace weeds while they grow and their residues can further suppress weeds (Evers, 1983; Hoffman et al., 1996; Smeda and Weller, 1996; Moyer et al., 2000). Weed control is usually best from dense cover crop plantings and when cover crops are allowed to grow for the longest time possible (Smeda and Putnam, 1988). Rye residues are among the most effective mulches and have been reported to suppress weed growth for up to 6 weeks after rye desiccation (Putnam et al., 1983; Barnes et al., 1987; Price and Baughan, 1987; Weston, 1990; Williams et al., 2000). Cover crop suppression of weeds is better if cover crops are managed with no tillage than if tilled into the soil (Blum et al., 1997). Living cover crops (living mulches) have greater weed suppression capacity than dead ones, but are often competitive with direct seeded crops for light, water, and nutrients (Fischer and Burrill, 1993; DeHaan et al., 1997; Kandel et al., 1997). Living mulches are, therefore, most practical in transplanted horticultural crops, vineyards, and orchards (Infante and Morse, 1996; Bugg et al., 1996).

Increased seedling disease was found to be a main reason for decreased cotton (Rickerl et al., 1988) and sorghum [*Sorghum bicolor* L.) Moench] (Dabney et al., 1996) seedling growth following legume cover crops. Residues caused less disease when left on top of the soil than when mixed into the soil, but growth inhibition was caused by a combination of surface and sub-surface effects (Dabney et al., 1996). Waiting until the soil is warm plus delaying planting until 14 to 21 days after killing legume cover crops are the surest ways of avoiding disease problems associated with the damping-off pathogen *Pythium* (Grunwald et al., 2000). Row cleaners that remove surface residues can improve stand establishment of crops planted 5 to 14 days after killing cover crops (Dabney et al., 1996). In long term studies, cover crops have reduced populations of some soil-borne plant pathogens (Rothrock and Kendig, 1991; Liebman and Davis, 2000).

Cover crop impacts on arthropod pests are complex and depend greatly on cover crop species and management (Lewis et al., 1997). Legume cover crops generally increase cutworm populations (*Agrotis* and *Peridroma* spp.), but these pests can be managed by killing cover crops 3 to 4 weeks prior to planting (Leonard et al., 1994) or by banding pyrethroid insecticides at planting. Legume cover crops are early season hosts of major pests of cotton (*Gossypium hirsutum* L.) and horticultural crops including tarnished plant bug (*Lygus lineolaris* (Palisot de Beauvois)) and the Heliothine complex of corn earworm (*Helicoverpa zea* (Boddie)) and tobacco budworm (*Heliothis virescens* (F.)) (Stadelbacher, 1981; Snodgrass et al., 1984). Cover crop management can affect the build up of these pests that will later attack crops. Early dessication of cover crops by mowing or herbicide spraying allows the cover crop to act as a trap crop in which portions the F1 generation are destroyed before they can mature (Snodgrass and Stadelbacher, 1994). Laub and Luna (1991) found that mowing cover crops was more effective than herbicide spraying for the control of armyworm (*Pseudaletia unipuncta* (Haworth)) when corn was no-till planted into a killed rye cover crop. If cover crops regrow and reform flowers, a second mowing may be needed to control tarnished plant bugs (Snodgrass and Stadelbacher, 1994).

In the Mississippi Delta, tarnished plant bug overwinters as adults. The earliest F1 nymphs appear on host plants during mid-March. Preferred tarnished plant bug hosts between January and April include: vetchs (*Vicia* spp.); spotted burclover (*Medicago arabica* (L.) Hudson); and crimson clover (Snodgrass et al., 1984). In contrast, subterranean clover (*Trifolium subterraneum*) is much less attractive to tarnished plant bug (Bugg et al., 1990). Bollworm and budworm overwinter as pupae and F1 larvae begin appearing in mid-April. For the earliest heliothine pest (bollworm), termination of cover crops prior to about 10 May prevents pupation of the F1 generation. It is therefore desirable that reseeding legume cover crops be early enough to produce hard seed prior to this date. Research is presented later that evaluates winter legume cover crops that may flower and mature earlier than crimson clover. Depending on the timing and species, allowing cover crops to flower and reseed may create opportunities for populations of

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Soil Carbon

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Nitrogen Fertility

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Cover Crops and Soil Quality

Cover crops affect several important aspects of soil quality. In this review the following aspects are addressed: soil carbon, nitrogen fertility, mycorrhiza, soil water, and soil temperature.

Soil Carbon

Cover crops increase carbon inputs into agricultural systems (Reeves, 1997; Kuo et al., 1997). This can result in carbon sequestration and increased soil quality (Derpsch et al., 1986; Lal, 1997; Lal et al. 1998; Reicosky and Forcella, 1998; Delgado et al., 1999). Combinations of increased carbon inputs together with reductions in tillage are needed to maximize increases in soil organic carbon (Roberson et al., 1991; Wright et al., 1999). Nitrogen is needed (is immobilized) to balance organic carbon in the formation of soil organic matter (Kuo et al., 1997). This can temporarily increase optimum N requirement in reduced tillage systems that sequester carbon in soils. Cover crops can contribute this N either by scavenging residual N or by N_2 fixation by legumes.

Cover crops increased soil organic matter, macroporosity, mean aggregate size, soil permeability, and crop yield in a 25-year conventional tillage cotton study (Patrick et al., 1957). Even where aggregate size distribution is not changed, cover crops can increase soil microbial biomass C and enzymatic activity (Mendes et al., 1999). Deep rooted cover crops, such as lupin (*Lupinus angustifolius* L.) can be particularly effective in increasing effective root depth and subsoil water storage capacity (Reeves, 1994; Calegari and Pavan, 1995; Chan and Heenan, 1996; Reeves, 1997). By utilizing water and by holding together soil structural units, cover crops improve a soil's capacity to carry machines and improve field accessibility (Känkänen, et al., 1998). However, depending on soil type and management, cover crops may have less impact on soil porosity and hydraulic conductivity than does wheel traffic (Waggoner and Denton, 1989).

Nitrogen Fertility

Synchronization of cover crop N release compared with demand by the following crops is needed for efficient production. If release and uptake are not synchronized, yields may be reduced and risks of high post-harvest soil NO_3^- -N con-

centrations and potential leaching losses may be increased (Meisinger et al., 1991; Torbert and Reeves, 1991).

Release of N from cover crops depends on species, growth stage, management, and climate. Lignin, carbohydrates, and cellulose content can affect the rate of N release from the cover crop residues (Muller et al., 1988; Bowen et al., 1993; Quemada and Cabrera 1995a). Residues with C:N ratios greater than 35 cause immobilization of N and slower N release rate (Pink et al., 1945, 1948). In general, high C:N ratio cereal grain cover crops immobilize soil N, increasing the amount of fertilizer N required for maximum economic yield of subsequent crops of corn, sorghum, and cotton (Mitchell and Teel, 1977; Frye et al., 1985; Brown et al., 1985; Hargrove, 1986; Waggoner, 1989b; Holderbaum et al., 1990; Doran and Smith, 1991; Sullivan et al., 1991; Decker et al., 1994). An early spring kill of cereal grains reduces accumulation of C more than of N, so the rate of release of cover crop N into following crops is faster (Huntington et al., 1985; Waggoner, 1989a; Evanlyo, 1991).

Legume cover crops usually have C:N ratios lower than 20 and reduce the amount of fertilizer N required for a given yield level (Touchton et al., 1982; Ebelhar et al., 1984; Doran and Smith, 1991). However, since yield potential is increased, legume cover crops sometimes do not reduce the economically optimum fertilizer level (Frye et al., 1985; Dabney et al., 1989; Utomo et al., 1990). Allowing legumes to grow beyond flowering usually does not increase the amount of N available to subsequent crops because of slower mineralization of cover crop biomass and because a fraction of the cover crop N may be tied up in hard seed (Waggoner, 1989a; Waggoner, 1989b; Ranells and Waggoner, 1992).

Release of cover crop N is faster if the cover crop residues are incorporated with tillage (Wilson and Hargrove, 1986). The slower N release from cover crop residues left on the soil surface is more pronounced in dry than in wet years, is most evident during the first 4 to 8 weeks after killing, and differences due to tillage in accumulative N release disappear after 16 weeks (Varco et al., 1989). Rapid mineralization may be an advantage in some situations where crop demand is rapid (Huntington et al., 1985; Waggoner, 1989b; Lemon et al., 1990). In other situations, slower release may be advantageous. Crops like cotton that have relatively long growing seasons and a peak N demand occurring after mid-bloom (Ebelhar, 1990), 11 to 12 weeks after planting in the mid-South (Oosterhuis, 1990), may make good use of slowly-available cover crop N in no-till systems. In Canada, synchrony of N release from summer-killed alfalfa to a subsequent spring wheat crop was better with no-tillage management than with tillage (Mohr et al., 1999). In dry-seeded rice culture, flooding 30 days after planting led to denitrification loss of soil NO_3^- -N while cover crop N recovery and rice yield were improved by no-tillage management (Dabney et al., 1989).

Ammonia (NH_3) volatilization has been suggested as a potentially important N loss mechanism from cover crop residues left on the soil surface in no-till

WINTER COVER CROPS

systems (Sarrantonio and others). The data cited below suggests that cover crop N content. Dabney and others found that N contents from an alfalfa field were related to accumulative NH_3 losses were. Also using micrometeorological data, Dabney and others found that losses from a crimson clover cover crop were. Losses in the 16 days following cover crop kill. Cabrera (1995a) studied N release from three cereal cover crops in no-till systems with periodic leaching. After 16 weeks, 92% of eventual clover NH_3 -N losses were. During this period, NH_3 -N losses were. Losses accounted for 37% of total N. Applied crimson clover residues reduced N losses without leaching. Quemada and others found a loss of about 6% of residues as NH_3 escaping from surface. While during wet periods, N losses were. Small losses of cover crop N.

Mycorrhiza

Mycorrhizal fungal associations have become widely recognized in agriculture. Soil (Galvez et al., 1995). Arbuscules with plant roots that are. (1999) found that a glycoprotein is involved in the development of soil aggregates. Management and active root growth. Fungi are also important in soil aggregation, particularly cotton (Zak et al., 1999). Growth and yield of cotton are improved with earlier and greater root growth. Seedling cotton roots benefit from mycorrhizal hyphae that developed in soil. When seedlings from conventional tillage are planted, higher mycorrhizal colonization rather than moving with the soil. Factor was more associated with soil. Related seedlings. Killing cover

Mycorrhizal fungal activity is a soil quality factor that has only recently become widely recognized. Cover crops increase inocula of mycorrhizal fungi in soil (Galvez et al., 1995). Arbuscular mycorrhizal fungi form symbiotic relationships with plant roots that can assist with water and nutrient uptake. Wright et al. (1999) found that a glycoprotein, glomalin, produced by these fungi, is central to the development of soil aggregate stability and that a combination of no-tillage management and active root growth is needed for maximum effect. Mycorrhizal fungi are also important in enhancing early growth and survival of some crops, particularly cotton (Zak et al., 1998). Flint (1999) found that enhanced early growth and yield of cotton planted into a killed wheat cover crop was correlated with earlier and greater root infection with mycorrhizal fungi. He postulated that seedling cotton roots beneficially tap into the existing network of mycorrhizal hyphae that developed in association with the wheat cover crop's root system. When seedlings from conventional and no-till treatments were mutually transplanted, higher mycorrhizal colonization remained associated with the no-till plot rather than moving with the no-till seedlings (Flint, 1999). This growth enhancing factor was more associated with the bulk of the soil than with inoculation of isolated seedlings. Killing cover crops too early may starve mycorrhizal fungi and

diminish this soil quality factor. This may be the reason why Elmore et al. (1992) found a wheat cover crop killed 4 to 6 weeks before soybean planting soybean had no impact on soybean growth or yield.

Soil Water

While cover crops may increase water infiltration into soil and soil water holding capacity, they also use water to grow and can potentially reduce yields of the subsequent crop in rainfed semiarid regions by reducing soil water content at planting (Reeves, 1994; Unger and Vigil, 1998). This is less of a problem in humid areas and where irrigation water is available to make up for water deficits at planting time. Summer water conservation by cover crop residues may be more important than spring water depletion by growing cover crops in determining final yield (Campbell et al, 1984; Clark et al., 1997b) if early season water deficits do not delay crop establishment (Ewing et al., 1991). Early killing of the cover crop is a management alternative that can improve soil water management where risks of N leaching are minimal (Unger and Vigil, 1998). Dabney (1998) gives a review of cover crop impacts on hydrology.

Soil Temperature

If incorporated into the soil by tillage, cover crops have little impact on soil temperature. In contrast, living cover crops and cover crop mulches can significantly alter soil temperature. Although plastic mulches increase daily maximum soil temperatures, organic mulches reduce them (Vos and Sumarni, 1997). Reduced daily maximum temperatures can be detrimental in cool regions where crop growth is temperature limited (Janovicek et al, 1997; Drury et al., 1999; Hoyt, 1999). On the other hand, reduced maximum temperatures can be positive in hot regions (Derpsch et al., 1991; Thiagalingam et al., 1996; Orr et al., 1997). During the winter cover crops increase soil temperatures (Calkins and Swanson, 1998).

Although it has been suggested that dark colored mulches (ie. hairy vetch) should allow more rapid soil warming than light colored mulches (ie. wheat straw), research has shown that mulch color has only a slight impact on soil warming. Black mulches increased sensible heat flux into the atmosphere rather than into the soil, and the difference in soil temperature at 0.05 m depth between black and white straw mulches was only 0.5°C (Sharratt and Flerchinger, 1995).

Standing cover crop residues result in higher soil temperatures than flat residues (Fortin and Hamill, 1994). When crops are planted at the cool part of their adapted zone, row cleaners that remove residues and cover crops from the planted area can help improve crop stands (Reeves, 1994; Janovicek et al, 1997; Kaspar

WINTER COVER CROPS

and Erbach, 1998). For daily maximum temperature (Stone et al., 1999). However, impacts can be caused (1997). In these situations, the impact is more significant than daily maximum

Based on the previous fill identified knowledge (1) to identify cold-hardiness to the mid-South of the compared to conventional (3) evaluate the effect of field trials as a function

Cover crop germination and hard seeded characteristics (Fine-silty, mixed, acid Hardiness Zone 7A: C Reported hear are a species that successfully resist *balansae*), and south legumes rye and ryegrass the variation in growth at the test site. Duplicate by broadcasting seed stage was recorded at killed with a herbicide (12 to 18 days after first killed 3 weeks later and recorded oven dry We determined residue several years during the volunteer cover repeated on new area

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er crops from the planted
vicek et al, 1997; Kaspar

and Erbach, 1998). For crops with meristems located below the soil surface, lower daily maximum temperatures is well correlated with slower seedling growth (Stone et al., 1999). However, in crops with epigeal germination, cool temperature impacts can be caused by chilling injury, disease, or insect damage (Brust et al., 1997). In these situations, daily minimum soil temperatures may be more important than daily maxima. This is an area where additional research is needed.

Objectives

Based on the preceding literature summary, research was undertaken to help fill identified knowledge gaps. The objectives of the studies reported herein were (1) to identify cold-hardy, early-maturing, reseeding legume cover crops adapted to the mid-South of the U.S., (2) determine the impact of no-till plus cover crops compared to conventional tillage on soil temperature at cotton planting time, and (3) evaluate the effectiveness of cover crops for nutrient scavenging in on-farm field trials as a function of species, planting date, and cropping system.

MATERIALS AND METHODS

Cover crop germplasm was screened for winter hardiness, early maturity, and hard seeded characteristics in replicated plots on a Grenada silt loam soil (Fine-silty, mixed, active, thermic Glossic Fragiudalfs) in Senatobia, MS (USDA Hardiness Zone 7A; Cathey, 1990). 'Tibbee' crimson clover was used as a check. Reported here are a subset of a larger screening experiments comprising entrants that successfully reseeded for several years: 'Paradana' balansa clover (*Trifolium balansae*), and southern spotted burclover. Also reported are growth of non-legumes rye and ryegrass (*Lolium multiflorum* Lam.) that provide an indication of the variation in growth potential of nonlegume cover crops without N fertilization at the test site. Duplicate plots (2 m by 5 m) of each cover crop were established by broadcasting seed onto a prepared seedbed and rolled in early October. Growth stage was recorded at least weekly beginning in December. Half of each plot was killed with a herbicide 7 to 10 days after Tibbee crimson clover reached full bloom (12 to 18 days after first bloom, second or third week in April). The other half was killed 3 weeks later (early May). We collected biomass samples at each kill date and recorded oven dry weight. No-till cotton was planted after the last kill date. We determined reseeding success by counting volunteer populations in the fall for several years during which additional seed production was prevented by killing the volunteer cover crops each spring prior to first bloom. The experiment was repeated on new areas each year from 1990-1991 through 1993-1994.

On a nearby area of the same soil used in the cover crop screening, soil temperature measurements were made during May 1993 in conventional and no-till plots in an experiment described by Triplett et al. (1996). The no-till treatment had a wheat cover crop that had been desiccated with a herbicide two weeks prior to initiation of temperature measurements on 6 May 1993. The conventional tillage treatment had no cover crop; the soil had been chisel plowed, disked, and had rows hipped. At planting on 10 May, the conventional tillage treatment had the rows partially smoothed with a do-all, while the no-till was planted flat. Four thermistor probes were placed at 2.5 cm depth in each treatment and temperature was recorded every hour during a 2 week period immediately prior to and following cotton planting. Daily minimum and maximum temperatures for each probe were compared using analysis of variance to test for significant differences between treatment means.

In eight on-farm trials in South Central Colorado during the winter 1994–1995, we studied the potential use of winter cover crops under organic carrot (*Daucus carota*), spinach (*Spinacia oleracea* L.), lettuce, and potato production systems. Nutrient uptake studies were conducted on irrigated soils classified: San Luis (fine-loamy over sandy or sandy skeletal, mixed, Aquic Natrargid); Kerber (coarse-loamy, mixed, frigid Aquic Natrargid); Gunbarrel (mixed, frigid Typic Psammaquent); and Shawa (fine-loamy, mixed, frigid Pachic Haploboroll) (Table 2). All these sites were under conventional tillage, and winter cover crops were incorporated after spring herbicide desiccation. All crops were under center pivot sprinkler irrigation, except spinach, which was grown as a surface irrigated field. In studies one through six, two transponders were placed permanently at each site so that the same areas within these plots could be sampled at each sampling period. At each site, four 21 m² plots were located under the same sprinkler span to minimize any possible variability between sprinkler nozzles from span to span. Soil and plant samples were collected at random in studies seven and eight. We present the total N and C content of cover crops at the last sampling except as noted below.

Organic carrots received 4.5 Mg ha⁻¹ y⁻¹ of poultry manure (77 kg N ha⁻¹). Additionally, about 38 kg NO₃⁻-N ha⁻¹ was added with irrigation water. Inorganic N fertilizer was applied to lettuce and potato at 153 and 213 kg N ha⁻¹, respectively. No reports about N fertilizer applied to spinach were obtained. Irrigation water added 27 kg NO₃⁻-N ha⁻¹ to lettuce and 36 kg NO₃⁻-N ha⁻¹ to potato. At the spinach site, NO₃⁻-N in the irrigation water was at trace levels. Total N uptake was 97, 162, 181, 99 kg N ha⁻¹ for carrots, spinach, potato and lettuce, respectively.

Soil samples were collected in each plot during the fall after harvesting of lettuce, spinach, potato or organic carrot; and during the spring after winter cover rye kill. At each time, soils were sampled in 0.3 m intervals to 1.5 m depth. The 0 to 0.9 m data are presented here. Plant samples for rye were collected by harvesting 0.4 m² in each plot before spring kill.

Table 2. Effect of Winter Cover Crops on NO₃⁻-N Mining for Different Cropping Systems of South Central Colorado

Cover Crop Content	Soil NO ₃ ⁻ -N	
	Fall	Spring
Winter	Time ¹	Dry

the fall after harvesting of the spring after winter cover intervals to 1.5 m depth. The rye were collected by har-

Study No.	Cropping System	Winter Cover Crop	Time [§] of Planting	Soil [§] Texture	Dry Matter (kg ha ⁻¹)	Cover Crop Content		Soil NO ₃ ⁻ -N		Soil Type	
						C	N	Fall	Spring		
						(kg ha ⁻¹)		(kg ha ⁻¹)			
1	Organic carrots	Rye	Ep	ls	1911 [†]	710 [†]	57 [‡]	49	28*	Kerber	
2		Rye	Ep	l	6642	2672	296	829	556*	Shawa	
3		Rye	Lp	ls	690	296	27	N/A	134	Gunbarrel	
4		Potato	Rye	Lp	809	327	31	77	68*	Gunbarrel	
5		Lettuce	Rye	Ep	si	7399 [‡]	2798 [‡]	178 [‡]	171	18***	San Luis
6		Lettuce	Rye	Ep	ls	4814 [†]	1800 [‡]	95 [‡]	103	11***	Kerber
7		Lettuce	Wheat	Lp	ls	454	194	18	225	204**	Kerber
8		Lettuce	Wheat	Ep	ls	2203	864	74	150	83***	Kerber

Estimated using 25% dry matter content belowground (Delgado et al., 1999).

winter cover wheat that was
wheat was grazed by horses
Above ground and below
1995, 15 February, 1996,
even and eight are from the
of grazing.
soil depth increment were
age weight and volume of
99). Sieved samples were
nent of the extracts were
on analysis. Plant samples
content by automated com-
Statistical analyses were
cedure (SAS Ins., 1988)

N
g the first two weeks of
flowering dates recorded
observations were made
interpreted as indicating

d spotted burclover were
d more successfully than
was probably due to two
e fact that this hard seed

a, Mississippi

1993	1994
4/10	4/11
4/1	3/26
3/7	3/30
4/26	After 4/18
4/2	4/8
4/10	4/12
4/26	

WINTER COVER CROPS

1235

Table 4. Above Ground Biomass (kg ha⁻¹) of Cover Crops in Late April at Senatobia, Mississippi

Cover Crop	1991	1992	1993	1994
'Tibbee' crimson	1390	8370	3590	2460
'Paradana' balansa	3800	5670	3280	1820
Spotted burclover	4790	na [†]	2480	3530
'Gulf' annual ryegrass	4700	2220	2510	1420
'Abruzzi' rye			2480	na
'Elbon' rye			1770	1440
'Rymin' rye			1860	

[†] Not available.

was produced prior to the time of growth termination that was tied to the flowering of crimson clover. As shown in Table 3, Paradana balansa clover bloomed and was about two weeks earlier than Tibbee and southern spotted burclover was even earlier, although it bloomed over a longer period of time. Early bloom dates allowed seed to mature and harden prior to growth termination. As previously noted, early termination can be an asset in cropping systems where cover crops are used as trap crops in IPM management of heliothine pests. Biomass production of these cover crops is similar to that of crimson clover (Table 4) and is at least double that produced by volunteer winter vegetation (weeds).

The large degree of variation in the flowering (anthesis) time of cereal rye was noted. Among three rye cultivars examined, 'Abruzzi' was the earliest. It was nearly two weeks earlier than 'Elbon' and four weeks earlier than 'Rymin' (Table 3). 'Gulf' ryegrass and Rymin rye all bloomed two to three weeks later than Tibbee. Elbon flowered about the same time as Tibbee. These differences in maturity are important when considering the time of killing of cover crops. It is desirable to have sufficient persistent and/or erect residue produced to protect the soil and to control wind and water erosion before killing cover crops. It is difficult to do this with later maturing cover crops and still plant crops like cotton at their optimum time.

Soil Temperature

While it is commonly stated that cover crops keep the soil cool, in this study they mainly decreased the amplitude of diurnal temperature fluctuations rather than the mean temperature (Fig. 1). Prior to planting on 10 May, minimum soil temperatures were warmer in no-till than in conventional till beds while maximum temperatures were cooler. During this period, the soil was warming and mean soil temperatures were not significantly different between tillage systems.

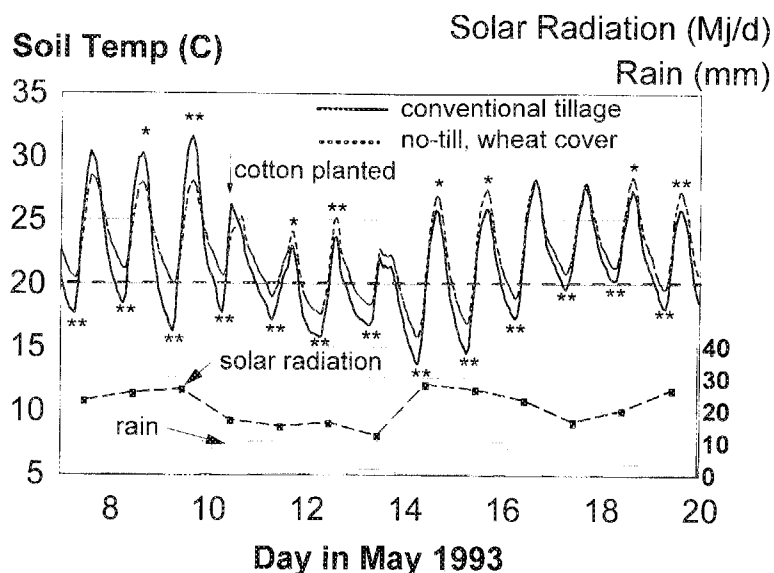


Figure 1. Average of 4 observations of soil temperature at 2.5 cm depth in conventional-till and no-till areas are presented with daily rainfall and solar radiation totals. The 20° reference line is the morning temperature minimum recommended for planting. Significant differences between tillage temperature minima and maxima are shown as * ($P < 0.05$) and ** ($P < 0.01$).

After planting, when the conventionally tilled beds were flattened and consolidated by rain and a cool cloudy period occurred, the cover crop mulch kept the no-till soil warmer (slowed cooling). This helped to improve cotton stand establishment and later yield (Triplett et al., 1996). Coldest minimum temperatures occurred on clear nights on 14 and 15 May. Periods of cool weather are a common risk after planting cotton and pose threats of seedling damage and disease. It is usually recommended that planting be delayed until the soil temperature in the morning exceeds 20°C with a favorable five-day forecast. As seen in Fig. 1, once this condition was met with no-till, risks from a change in the weather were reduced.

Nitrogen Scavenging

Although organic carrots had lower residual soil NO_3^- -N than spinach and lettuce (Table 2 $P < 0.05$), cover crops were capable of scavenging the residual soil NO_3^- -N in these systems ($P < 0.05$). The N uptake of these cover crops varied

from 57 to 296 kg N ha⁻¹ after planting (Table 2). The N from the middle of May to the middle of June had C:N ratios lower than 20:1, so crop N will be quickly immobilized (et al., 1985; Waggoner, 1990). That 50% of the N in the cover crops could have contributed to Central Colorado. Since carrots, spinach, potatoes, and scavenge and potential N-fixing crops. Early planted dry biomass production of planted covers (Table 2) had a significant impact in potentially decrease potential

Other

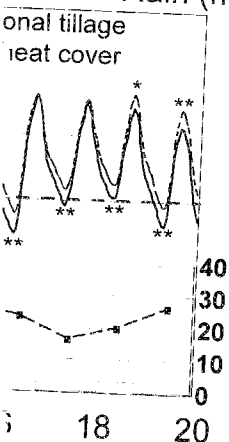
Cover Crop Adaptation

Temperature and soil moisture are important in crop selection and planting. The warmer and wetter the climate, the greater the number of cover crop species that can be grown.

Small seeded legumes are easier to drill and are therefore a good choice for a standing crop may be drilled after harvest. Wheat can be problematic to drop (Sanford, 1979; Triplett et al., 1996).

Rye is the most common and the earliest to be established. It is hardy than rye, hairy vetch, and it also has the highest N-fixing capacity. Winter ground cover crops of seedling legumes like sweetclover [*Melilotus alba* L.), vetch [*Vicia sativa* L.), and

ar Radiation (Mj/d)
Rain (mm)



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NO_3^- -N than spinach and
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from 57 to 296 kg N ha⁻¹ for early planting and from 18 to 31 kg N ha⁻¹ for late planting (Table 2). The farmers killed the cover crops at an early growth stage, from the middle of March to the first week of April. This should have kept the C:N ratios lower than 20, so we can assume that significant amounts of the cover crop N will be quickly mineralized and recycled to the following crop (Huntington et al., 1985; Waggoner, 1989a; Evanlyo, 1991; Doran and Smith, 1991). Assuming that 50% of the N in the crop residue can be recycled, the early planted cover crops could have contributed 25 to 132 kg N ha⁻¹ to subsequent crops in South Central Colorado. Since the average N uptake was 97, 162, 181, 99 kg N ha⁻¹ for carrots, spinach, potato and lettuce, respectively, early planted cover crops can scavenge and potentially recycle a significant fraction of N needed by the following crops. Early planted cover crops, with more growing degree days, had higher dry biomass production with a higher organic carbon and N content than late planted covers (Table 2; $P < 0.05$). However, late planted cover crops can still have a significant impact in the protection of soil and water quality since they significantly decrease potential soil erosion (Delgado et al., 1999).

Other Considerations in the Practical Selection and Management of Cover Crops

Cover Crop Adaptation and Establishment

Temperature and rainfall are the primary climatic variables affecting cover crop selection and potential utility (eg. USDA, 1948; SAN, 1998). The warmer and wetter the climate, the greater the potential benefits of cover crop and the greater the number of options available.

Small seeded legumes are more sensitive to timely rainfall at planting than larger seeded cover crops (Keeling et al., 1996). Broadcasting seed is faster than drilling and is therefore attractive to farmers. If done early, broadcast seeding into a standing crop may result in better stands and more early cover crop growth than drill seeding after harvest (Frye et al., 1988). However, establishment of broadcast wheat can be problematic unless done into a fully closed crop canopy prior to leaf drop (Sanford, 1979; Griffin and Taylor, 1986).

Rye is the most cold tolerant, the easiest to establish, the most productive, and the earliest to head among temperate region cereal cover crops. Although less hardy than rye, hairy vetch is the most cold hardy of annual legume cover crops; it also has the highest N percentage. Mixtures of rye and vetch provide more early-winter ground cover than either alone (Holderbaum et al., 1990). Cold hardiness of seedling legumes has been reported in the following order: hairy vetch, yellow sweetclover [*Melilotus officinalis* (L.) Pall.], crimson clover, black medic (*Medicago lupulina* L.), white clover (*Trifolium repens* L.), subclover, barrel medic

(*Medicago trunculata* Gaertn.), and snail medic [*Medicago scutellata* (L.) Mill.] (Brandsaeter et al., 2000). In an Ohio, USA study (Creamer et al., 1997), fall seeded rye, barley (*Hordeum vulgare* L.), crimson clover and hairy vetch dependably overwintered while 'Nitro' alfalfa (*Medicago sativa* L.), ladino clover (*Trifolium repens* L.), subterranean clover, Austrian winter pea (*Pisum sativum* ssp. *Arvense* (L.) Poir), and annual ryegrass did not. In climates too cold to allow successful establishment of winter cover crops following crop harvest, alternative management techniques include overseeding cover crops into a winter cereal rotated with a summer crop (Dou and Fox, 1994). In warm climates, cold weather can be used as a natural way to kill summer planted cover crops, for example the tropical legume cover crop sunn hemp (*Crotalaria juncea* L.) (Mansoor et al., 1997).

Volunteer reseeding reduces establishment costs that have been estimated from \$63 to \$111/ha (Frye et al., 1985; Power et al., 1991; Kelly et al., 1995). Volunteer reseeding can result in earlier and more reliable cover crop stands than annual planting (Myers and Waggoner, 1991). Because crimson clover seed does not remain hard for longer than one year, in reseeding systems crimson clover makes seed every spring prior to planting a summer crop (Touchton et al., 1982). 'Tibbee' crimson clover (*Trifolium incarnatum*) has been among the earliest-maturing commercially-available cultivars grown in the Southeast (Boquet and Dabney, 1991). However, it makes seed too late (early to mid-May) to allow planting corn, cotton, or sorghum at their optimum dates. One solution is to select crops that may be planted later, such as tropical corn (Reeves and Wood, 1994). Another solution is to find cover crops that mature earlier or that do not need to produce seed every year.

Southern spotted burclover is the most winter hardy of the annual medics. It was used as a reseeding cover crop in the cotton belt forty years ago. It was allowed to reseed ahead of a late-planted corn crop and would then volunteer before three or four succeeding cotton crops (USDA, 1949). There were once at least three named cultivars of southern spotted burclover in commercial trade (USDA, 1951), however, today there are currently no commercial sources. Subterranean clover has also been used as a reseeding cover crop (Taylor, 1985; Evers et al., 1988; Graves et al., 1991; Dabney et al., 1989; Fairbrother, 1991; Komatsuzaki et al., 1998), but winter hardiness and early seed maturity appear to be negatively correlated in subterranean clover.

Paradana balansa clover is recommended as a promising commercially available reseeding winter legume cover crop for the Southeastern U.S. (Dabney, 1995). It has cold hardiness similar to 'Mt. Barker' subterranean clover: hardy throughout plant hardiness zone 7A but marginal in zone 6B. The balansa clover appears particularly well adapted to heavy clay soils with pH values above 6.5, but it is not considered adapted to highly alkaline soils (Beale et al., 1985). Seed imported from Australia is commercially available in the U.S. (sources listed in SAN, 1998). Because it has very small seed, as little as 5 kg seed ha⁻¹ has given

good stands. After one no-till cotton production cycle, the cover crop was established until the first winter

Winter cover crops can recycle residual soil N and potentially recycled into the soil as fixed N. When residual N is quickly and growth is robust, the system with cover crops can be established abundantly even if soil N is low. Planting results in greater N use efficiency and less N loss to the atmosphere. They can also reduce herbicide and insecticide use. Three weeks prior to planting subsequent crops with cover crops can increase soil water content. Cover crop temperature in no-till systems is higher than in conventional systems. Cover crop benefits are also related to the amount of hardiness zone. Effective ways of terminating cover crops and weed and insect control are also related to species selection, timing of cover crop N release to the soil.

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scutellata (L.) Mill.] (reamer et al., 1997), fall and hairy vetch (*Vicia villosa* L.), ladino clover (*Trifolium repens* L.), and pea (*Pisum sativum* ssp. *arvense*). In climates too cold to allow winter crop harvest, alternative crops into a winter cereal rye. In warm climates, cold weather cover crops, for example crimson clover (*Trifolium incarnatum* L.) (Mansoor

that have been estimated (1991; Kelly et al., 1995). In cool climates, winter cover crop stands than in warm climates. Crimson clover seed does not require a cold stratification period. Crimson clover makes a good winter cover crop (Mansoor et al., 1982). 'Tibber' is one of the earliest-maturing winter cover crops (Boquet and Dabney, 1991). It allows planting corn, soybeans, and other crops that require a cold stratification period (Wood, 1994). Another benefit of cover crops is that they do not need to produce

yield of the annual medic. In the last forty years ago. It was found that it would then volunteer (Mansoor, 1994). There were once at least 100,000 acres of crimson clover in commercial trade in the Southeastern U.S. Subsequently, crimson clover was lost to commercial sources. Subsequently, crimson clover was lost to commercial sources (Taylor, 1985; Evers and Mansoor, 1991; Koma and Mansoor, 1991). Crimson clover maturity appear to be

promising commercially in the Southeastern U.S. (Dabney, 1991). Mediterranean clover: hardy in the Southeastern U.S. (Dabney, 1991). The balansa clover (*Medicago sativa* L.) has pH values above 6.5, and is hardy in the Southeastern U.S. (Beale et al., 1985). Seed yield of balansa clover in the U.S. (sources listed in Table 1) has given

good stands. After one seed crop, volunteer stands have been excellent for 3 y in no-till cotton production. In reseeding years, the killing of balansa must be delayed until the first week of May (north Mississippi) and while this may delay establishment of the subsequent crops this will not be required every year.

CONCLUSIONS

Winter cover crops reduce wind and water erosion. They can scavenge and recycle residual soil NO_3^- -N and return significant amount of N that can be potentially recycled into the following crops. Legumes can contribute biologically-fixed N. When residual inorganic N is low, cover crops will scavenge most of this N quickly and growth will be N limited. Legume/cereal bi-cultures provide a robust system with capacity to scavenge both soil and atmospheric N and grow abundantly even if soil inorganic N is minimal. When inorganic N is high, earlier planting results in greater N scavenging than later planting. Cover crops can sequester atmospheric carbon, converting it to soil organic matter for improved soil quality. They can compete with and help control difficult to control weeds and reduce herbicide and other weed control costs. Allowing cover crops to grow until three weeks prior to planting permits mycorrhizal fungal associations to benefit subsequent crops without increasing risks of crop disease. Cover crops can reduce soil water content. Cover crop residues reduce diurnal fluctuations in soil temperature in no-till systems, decreasing the maximums and increasing the minimums compared to conventional tillage systems. Reseeding systems may provide cover crop benefits at reduced cost. Balansa clover is a promising reseeding legume for hardiness zone 6B and warmer. Mowing and rolling vegetation offer effective ways of terminating vegetation growth while managing cover crops for weed and insect control that reduce the need for pesticide inputs. Management of species selection, time of planting, and time of killing can potentially match cover crop N release to the following crop, helping to improve soil and water quality.

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Red soils belong to the soil order of the soil order of and continue to ment of China. larly deforestation degradation of tion in the red s oped to restore 1) reclamation lime, manures, tire rooting dep trench-planting organic material ers or lime; 4) m ize soil erosion